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Air entrainment by plunging turbulent jets: impact of jet roughness revisited.

Redor Ivan^a, Guyot Gregory^{a,b}, Obligado Martin^a, Matas Jean-Philippe^c, Cartellier Alain^a

^aUniv. Grenoble Alpes, CNRS, Grenoble-INP, LEGI, Grenoble, 38000, France

^bEDF Renewable Energy – Hydro Engineering Center, 73290 La Motte Servolex, France

^cUniv. Lyon, Univ Claude Bernard Lyon 1, CNRS, Ecole Centrale de Lyon, INSA Lyon, LMFA, 69622 Villeurbanne, France

Alain.Cartellier@univ-grenoble-alpes.fr

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Abstract

New experiments on plunging jets have been conducted to investigate the parameters controlling the entrained gas flow rate. On a small-scale experiment (jet diameter 7.6mm, jet velocity from 1 to 10m/s, fall height up to 0.5m), we quantified the entrained gas flow rates using conical and Doppler optical probes as well as the varicose and sinuous corrugations of the jet. These data were used to test Sene's 1998 model. On one hand, Sene envisioned an entrainment mechanism equivalent to a volumetric pump: we found his proposal valid for turbulent coherent jets with an interface deformation up to 0.4 times the jet diameter. On another hand, and contrary to Sene's model, the deformation was found to be linear in velocity so that the gas flow rate increases with the jet velocity square (and not as U_i^3). To test further Sene's proposal, we used a larger facility (diameter 2 to 20cm, impact velocities up to 22m/s, fall height from 2 to 9.5m) that give access to more complex jet topologies including stripped jets, aerated jets... Preliminary results gathered in such conditions will be presented and discussed.

Introduction

Air entrainment by plunging jets is receiving a renewed attention in hydroelectricity with e.g. issues related with safety (erosion downstream dams), energy production, or environment (oxygenation). Hence, a number of longstanding but still open questions (Bin, 1993; Kiger & Duncan, 2012) need to be revisited. Concerning the depth of penetration, we proposed a model (Guyot et al., 2020) that proves reliable from small to large jets. The present contribution deals with the gas flow rate Q_a entrained under the free surface.

Let us start from the model of Sene (1988) for rough jets. That model is based of two arguments. First, Sene argues that the entrained air is the air trapped within interface corrugations. Hence:

$$q_a = Q_a / L \propto U_i \varepsilon \quad (1)$$

where L is the length of the contact line between the jet and the pool, U_i is the jet velocity at impact and ε is a characteristic height of corrugations at impact. Second, in an analogy with sub-surface turbulence, Sene relates ε with velocity fluctuations normal to the interface, and for a jet of given turbulent intensity, he proposed:

$$\varepsilon \propto U_i^2 / g \quad (2)$$

Thus, the gas flow rate predicted by Sene writes:

$$q_a \propto U_i^3 / g \quad (3)$$

Ma et al. (2010) analyzed former experiments and found that Q_a increases as U_i^3 as predicted by eq.(3) except when there is "formation of an unstable air cavity". Although that result

is encouraging, the two steps in Sene's proposal have never been independently tested. Moreover, the interface deformation predicted by eq.(2) assumes that gravity is counterbalancing inertia. This argument is not relevant for vertical jets while most data examined by Ma et al. concern vertical jets. To clarify these issues, we undertook to test each of the two steps of Sene's reasoning using small and medium scale facilities.

Experimental Facilities and Measuring Techniques

Both facilities use air and water in ambient conditions. The small-scale facility consisted in a vertical jet (diameter $d_o=7.6\text{mm}$) impacting a large, deep pool. Velocity at injection V_o ranged from 1 to 10m/s and the height of fall h was varied from 0.4 to 40 d_o . For the medium size facility, d_o ranged from 23 to 213mm, and V_o was up to 25m/s (for $d_o \leq 100\text{mm}$). The height of fall was varied between 2m and 9.5m. The receiving basin is a 5m in diameter deep well. Measuring techniques consisted in optical probes to access bubble velocity and void fraction. Both conical probes that exploit the de-wetting time (Cartellier & Barrau, 1998) and Doppler probes (Lefebvre et al., 2022) were used. The local gas flux was evaluated by summing up all chord lengths detected during the measuring duration. The latter corresponds to 10^5 bubbles or to 180 sec. The gas flow rate was determined by spatial integration of the local flux. These measurements were achieved at short distances (3 to 5 d_o) below the free surface. Using a high resolution Phantom camera, sinuous (resp. varicose) deformations were quantified by the standard deviation of the jet center

position (resp. the jet diameter) versus h .

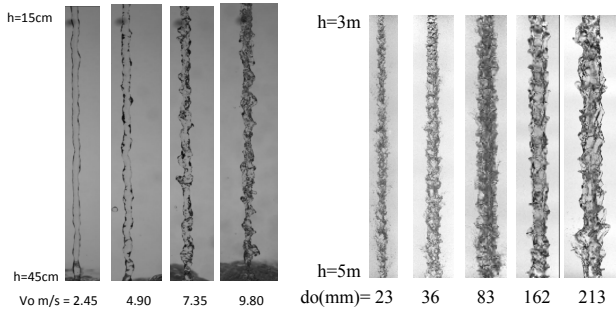


Figure 1: Jets produced in the small scale facility (left) and in the medium size facility (right).

Results and Discussion

For a fixed height of fall, Fig.2 provides $q_a = Q_a / (\pi D_i)$ where D_i is the jet diameter at impact versus U_i times the total deformation ϵ evaluated as the sum of sinuous and varicose contributions. The linearity suggested by eq.(1) happens to hold over one decade in abscissa: this supports Sene's vision of an entrainment mechanism equivalent to a volumetric pump.

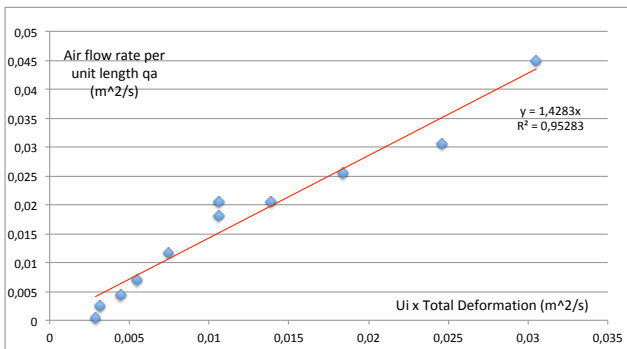


Figure 2: Gas flow rate per unit length versus $U_i \epsilon$ (small facility $h/D \approx 40$).

We also examined how the roughness ϵ evolves with the jet velocity. As shown in Fig.3, ϵ linearly increases with U_i : the quadratic dependency proposed by Sene in eq.(2) is not observed for the conditions considered here. In addition, the entrained gas flow rate increases here as U_i^2 and not as U_i^3 .

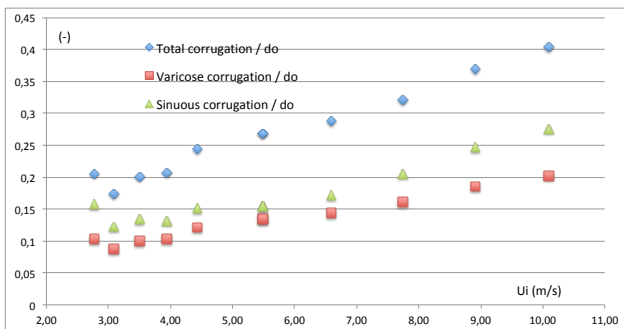


Figure 3: Roughness ϵ versus the jet velocity at impact U_i (small facility $h/D \approx 40$).

Conclusion

While revisiting Sene's proposal for the air flow rate entrained by a plunging jet, we found that his volumetric pump concept is indeed valid for turbulent coherent jets whose total corrugation ranges from 17% to 40% of the jet diameter. It would be worthwhile to consolidate these results over an enlarged data set in terms of jet corrugations, and to test if this approach remains applicable to different jet topologies such as those obtained in the medium scale experiment and illustrated in Fig.1-right. The latter notably include strong stripping, aerated jets or buckling jets. Preliminary data gathered in the medium size facility indicate that it could be so, provided that the effective corrugation height for air entrapment becomes a function of the jet topology.

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